Achieving milli-arcsecond residual astrometric error for the JMAPS mission

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ABSTRACT

The Joint Milliarcsecond Pathfinder Survey (JMAPS) is a small, space-based, all–sky, visible wavelength astrometric and photometric survey mission for 0^{th} through 14^{th} I-band magnitude stars with a planned 2013 launch. The primary objective of the JMAPS mission is the generation of an astrometric star catalog with 1 milliarcsecond (mas) positional accuracy or better, and photometry to the 1% accuracy level or better at 1^{st} to 12^{th} mag. Achieving this level of accuracy in the final catalog requires a demanding attention to reducing systematic effects.

We present our findings on distortion, signal to noise, and the astrometric bandpass necessary to obtain the desired accuracy for JMAPS.

Keywords: Space, Survey, Astrometry

1. DISTORTION ANALYSIS

The task of projecting the spherical sky onto a flat detector inevitably yields distortions. Inevitable manufacturing errors will also create deviations from the desired relationship between the astronomical positions (α, δ) and measured detector locations (x, y). A pair of "standard coordinates" (ξ, η) are defined[1] as:

$$\xi = \frac{\cos\delta \sin(\alpha - \alpha_0)}{\sin\delta_0 \sin\delta + \cos\delta_0 \cos\delta \cos(\alpha - \alpha_0)} \tag{1}$$

$$\eta = \frac{\cos\delta_0 \sin\delta - \sin\delta_0 \cos\delta \cos(\alpha - \alpha_0}{\sin\delta_0 \sin\delta + \cos\delta_0 \cos\delta \cos(\alpha - \alpha_0)} \tag{2}$$

where (α_0, δ_0) are the tangential point of the exposure. Use of standard coordinates is the same as assuming a gnomonic projection.

The JMAPS optical system is a three mirror anastigmat,[2] which can, to third order, eliminate spherical aberration, coma, and astigmatism. This type of design leaves a Seidel distortion pattern that needs correction. Manufacturing errors and gravity release can yield a decentering distortion that must be corrected for. Any assembly error can give a focal plane that is not perpendicular to the chief ray of the optical system, which will yield a further term to correct for.

A general equation, allowing for differing plate scales in the x and y axis, plate offset terms, rotation and non-perpendicularity of the axes, 3^{rd} order radial distortion, tilt and decenter terms can be written as

$$\xi = a_0 x + a_1 y + a_2 + a_6 x r^2 + a_7 x^2 + a_8 xy + a_9 r^2 \tag{3}$$

$$\eta = a_3 x + a_4 y + a_5 + a_6 y r^2 + a_7 xy + a_8 y^2 + a_{10} r^2 \tag{4}$$

where r^2 is defined as $x^2 + y^2$. The a_0 through a_5 terms are the normal 6 term plate solution, the a_6 represents the radial 3^{rd} order distortion, a_7 and a_8 are the "tilt terms" and a_9 and a_{10} are the decenter term.

The JMAPS error budget calls for a rms residual after subtraction of a 3rd order polynomial to be below 2 mas. In order to achieve this we must carefully measure and correct for not only the radial 3^{rd} order distortion, but tilt and the expected decenter from gravity release. Figure 1 shows a series of residual images with varying terms included.

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The requirements for low distortion after subtraction of distortion, tilt, and decenter terms drives the temporal stability requirements. The normal observing cadence has a 20 second exposure followed by a 10 second slew to the next observing point offset by half a field of view. The notional observing plan will have approximately half an orbit of continuous observing, followed by a large slew to the starting location for the next set of observations. For the 103 minute orbit of JMAPS, there are expected to be two series of 50 minute exposures, for a total of approximately 100 exposures. These 100 exposures will have the 6 term "plate solution" for each exposure, and a single distortion, tilt, and decenter term from a non-linear least square solution. The relative orientation of the 2x2 array of CMOS/CCD detectors must remain stable over this time period, which will require stability of tens of milliKelvins.

2. SIGNAL TO NOISE

Elliptical Gaussian fits are commonly used for accurate measurements of fundamental source parameters such as central position, peak and integrated fluxes, and angular size. As a rule of thumb, the errors in the x and y centroid positions scale as the Full Width Half Maximum (FWHM) of the stellar profiles divided by the signal–to–noise ratio.[3] JMAPS will use a series of non–destructive reads of 1, 4.5, and 20 seconds to cover the dynamic range of 6^{th} to 14^{th} magnitude, while exposures in the range of 3, 12, 50, and 200 milliseconds will cover the dynamic range of the brightest stars. Figure 2 shows the expected centroid accuracy for a blue star, a stellar type star, and a red star as a function of the seven nominal exposure times.

3. BANDPASS REJECTION

The JMAPS optical train is, except for the plane parallel window that supports the M2 mirror, a purely reflective system. This, in concert with the relatively narrow (200 nm) full width of the astrometric bandpass filter, will yield a system with low lateral color. However, to obtain the final catalog of 1 mas accuracy, it is important to keep the systematic effects well below 1 mas. Figure 3 shows the expected lateral color from a stellar image in the corner of the focal plane. To achieve the desired low systematic lateral color terms, not only must care be taken with the design of the optics, but care must be taken with the in and out of band transmissions of the bandpass filter.

In order to obtain satisfactory signal to noise in the detected stellar images, the throughput of the entire system (optical surfaces and detector quantum efficiency) must be high in the desired bandpass. Additionally, the system must reject light out of the desired bandpass to minimize the lateral color of the measured point spread function (PSF). We show an a representation of the desired astrometric bandpass in Figure 4.

4. CONCLUSIONS

The JMAPS telescope will produce highly precise astrometry and photometry for approximately 35 million stars. Extreme care must be taken to control and reduce systematic errors to ensure the final catalog can meet the required accuracies. The distortion present in the optical system must be subtracted out to the sub milliarcsecond level. We find that tilts and decenters must be accounted for in addition to the more common 3^{rd} order distortion. The filter that defines the JMAPS astrometric filter requires stringent limits on the in band and out of band transmissions to ensure high signal to noise images with low lateral colors.

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[3] Condon, J. J., "Errors in Elliptical Gaussian FITS," *Proceedings of Astr. Soc. Pac.* **109**, 166–172 (Feb. 1997).

5. FIGURES AND TABLES

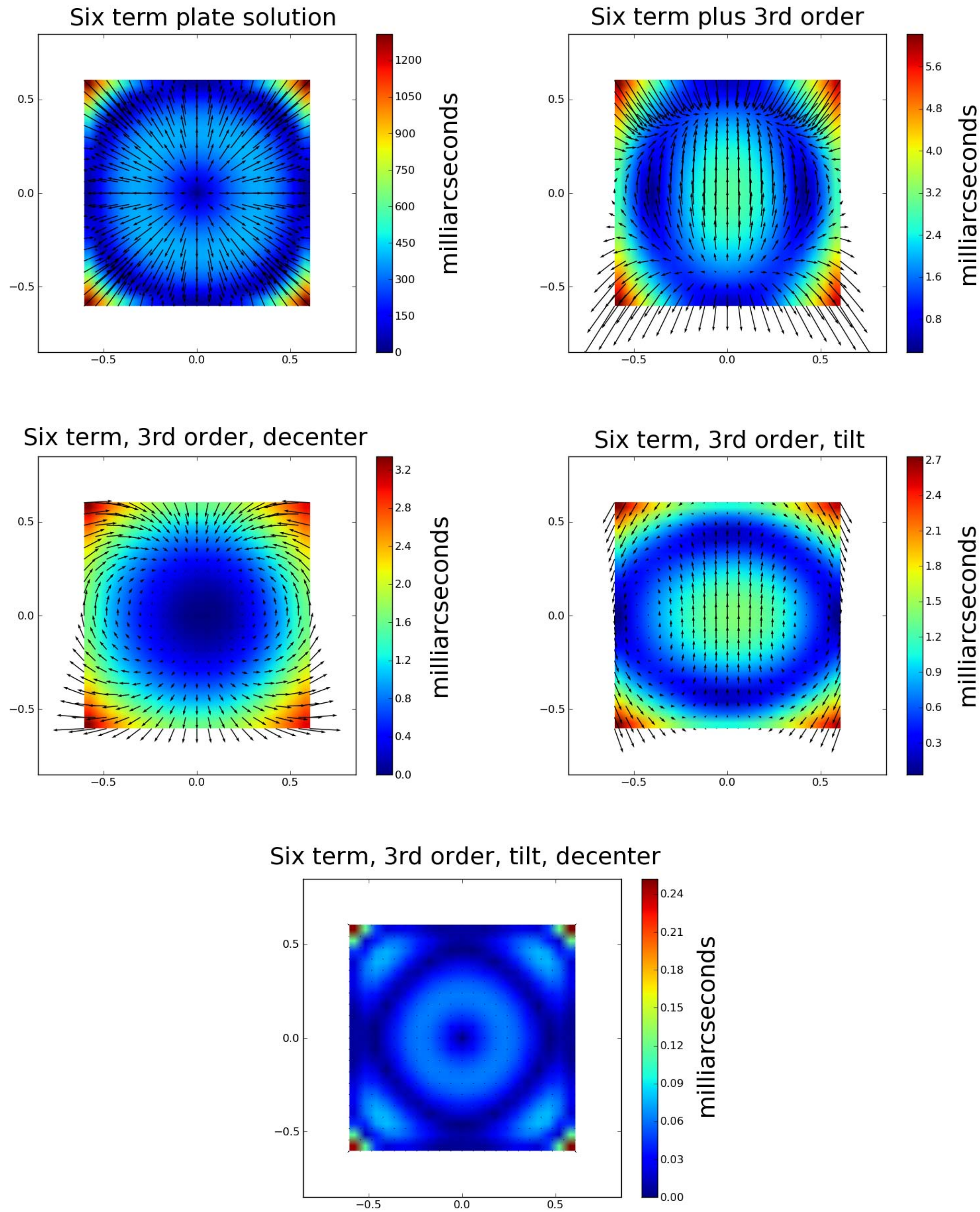


Figure 1. A sequence showing the reduction in the astrometric errors as the complexity of the fitting model increases. A no distortion model is shown in the upper left, and the complexity of the model increases until the final figure, which has a rms residual of approximately 0.02 mas.

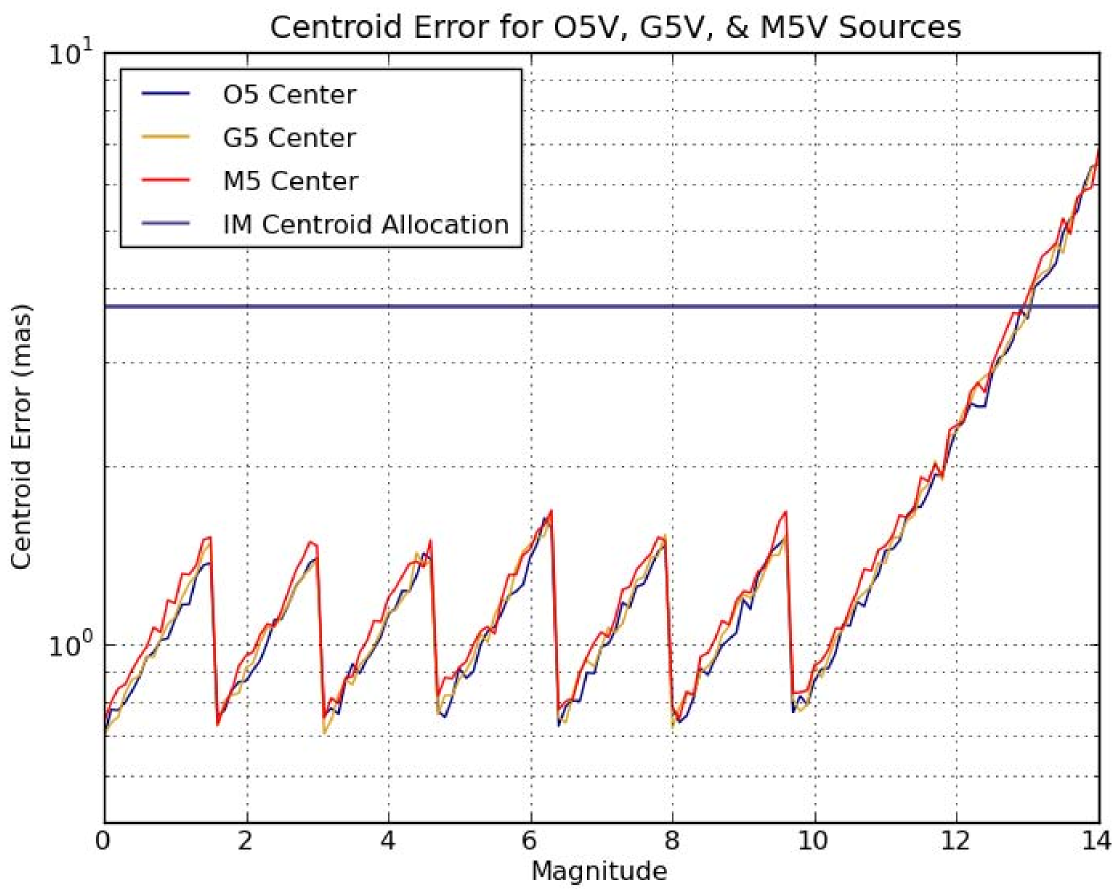


Figure 2. The expected centroid accuracy as a function of magnitude for three example stellar types. The sawtooth pattern shows the effect of non destructive reads and multiple exposure times.

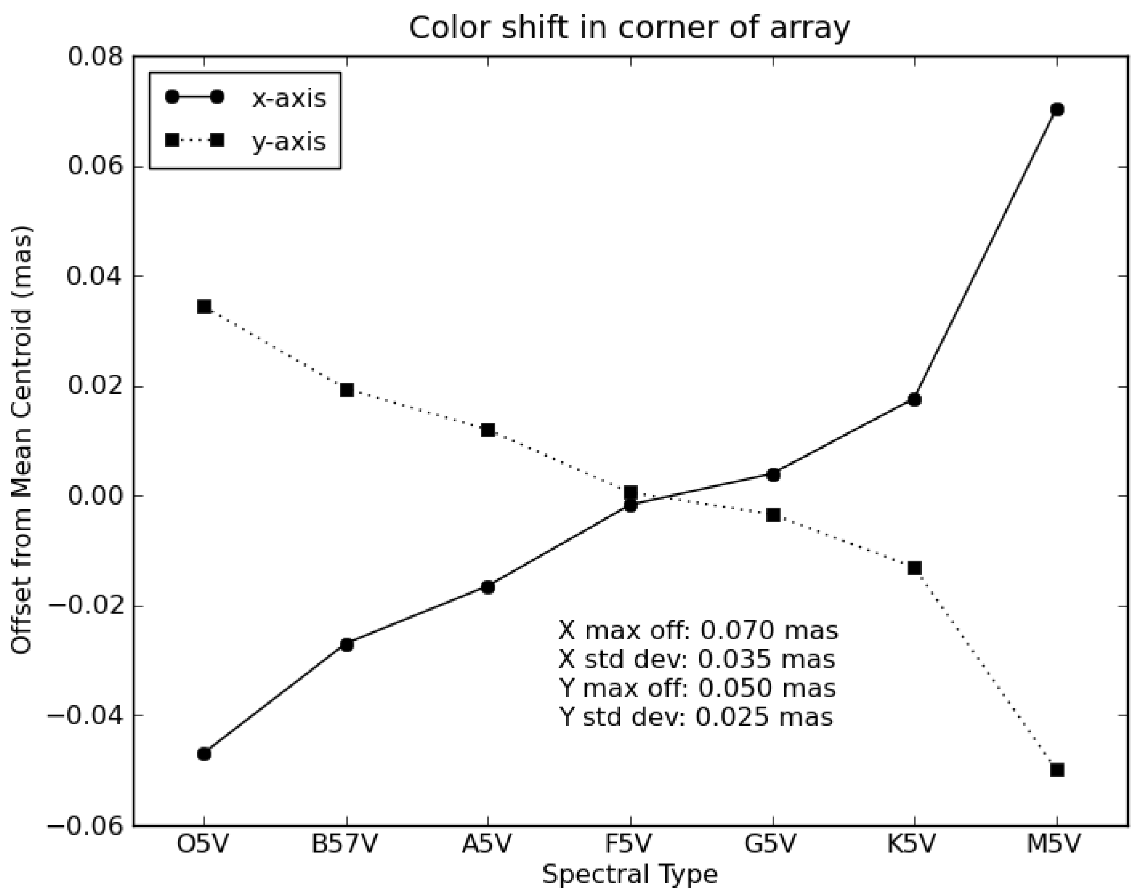
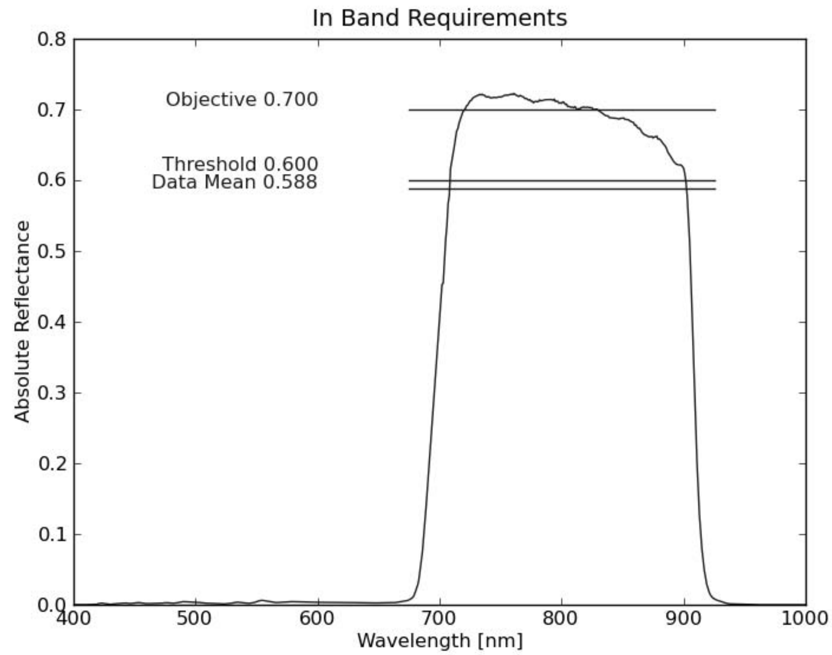


Figure 3. The expected lateral color, in mas, of a stellar image in the corner of the field of view.



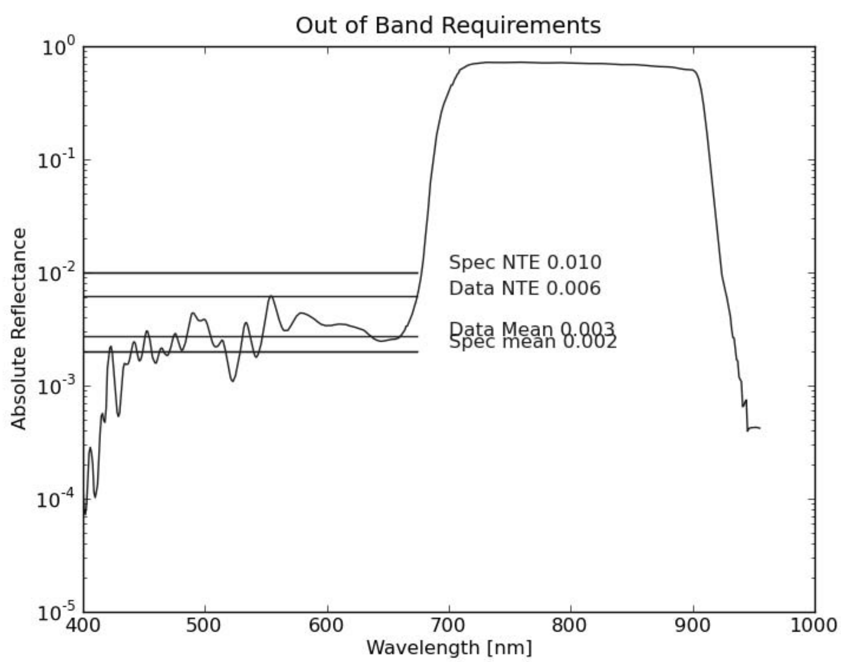


Figure 4. The system requirements of both the in band, and out of band throughput of an example astrometric bandpass prepared as part of a risk reduction activity for JMAPS. The throughput of the astrometric bandpass was combined with expected measurements of the throughput of an anti reflection coating, a long wave cutoff, 3 powered elements, five fold flats, and the quantum efficiency of the CMOS/CCD detector. The top figure shows a linear scaling to allow the in band requirements to be seen, while the lower figure is scaled logarithmically to allow the out of band requirements to be easily seen.